Power System Reliability Analysis Incorporating Distributed Generator

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Abstract

At the distribution stage, power system is susceptible to collapse and interruption due to weather associated issues and human mistakes. Reinforcing the distribution system with distributed generator (DG) as a supplementary power source guarantees the reliability of electric power supply to customers. This paper addressed the influence and impact of the DG installed as a supplementary or backup generator for the reliability improvement of a distribution circuit which was modeled after a residential distribution network of Government Residential Area (GRA) feeder line, Osogbo, Nigeria. The reliability improvement was evaluated by reliability indices that include SAIDI (System Average Interruption Duration Index), CAIDI (Customer Average Interruption Duration Index), ENS (Energy Not Supplied) and AENS (Average Energy Not Supplied) using MATLAB software package. Hence, the optimum locations for installation of different sizes of DG were determined and the value of placing DGs at various distances from the substation was investigated. When disconnects were applied on the main feeder line, the reliability contribution of DG as a backup generator was maximized and the overall system reliability increased. The reverse of which was the case when disconnects were not applied. The results of the simulations showed significant improvement in the indices due to the incorporation of the disconnects; for instance, SAIDI improved from 10.7765 hours/customer year to 6.724584 hours/customer year, CAIDI from 3.968557 hours/customer interruption to 2.476378 hours/customer interruption and ENS from 48474.64 kWh/year to 30240.64 kWh/year. The scenarios presented enhanced the reliability and resilience of the power grid as observed with the installation of different DG sizes at various distances from the sub-station.

Keywords: CAIDI, SAIDI, ENS, AENS, Reliability, Distributed Generators, Disconnects

1. Introduction

The power system is vulnerable to system abnormalities such as control failures, protection or communication system failures, and disturbances, such as lightning, and human operational errors. Therefore, maintaining a reliable power supply is a very important issue for power systems design and operation [1]. Those responsible for planning of electric supply systems are faced by difficult problem of deciding how far they are justified in increasing the investment on their facilities to improve service reliability [2]. Reliability is not a new topic in the electric power industry. Yet, it has attracted interest of professionals in the past decade due to incessant blackouts being experienced. Distributed generation is defined as a small-scale generation unit, i.e. 10MW or less that can be interconnected at or near the customer load. Distributed Generator (DG) is expected to play an increasingly important role in the future of power systems System reliability is a critical factor in distribution system's planning and operation. The reliability indices such as SAIFI (System Average Interruption Frequency Index), SAIDI, CAIFI(Customer Average Interruption Frequency Index), CAIDI, ASAI(Average System Availability Index), ENS and so on presented by the IEEE(Institute of Electrical and Electronics Engineers) guide are used to evaluate reliability of the system. In [3] the IEEE guide for reliability indices and terms and definitions related to them were presented. Several papers discussed the use of these reliability indices and the data collection for their evaluation [4] [5]. The location for the placement of DGs is of key importance. In [6] the authors explored the effects of DG on system reliability on a distribution system. The analysis revealed that reliability indices were highly sensitive to location. In [7] the author discussed the DG impacts on reliability, losses and voltage profile of the system. The paper showed that reliability indices could be improved by properly allocating DG. Properly coordinated distributed generation can have a positive impact on the system. The author of [3] presented the impacts (pros and cons) of DG on reliability indices and power condition. The favorable impacts included faster restoration and reduced voltage sags while the unfavorable impacts could be incessant tripping, increased fuse blowing etc. In [9] the author discussed the deliberate islanding impacts of DG for reliability improvement.

A small number of papers had presented validation models for calculating reliability indices [10] and [11]. In [10], the vital data for reliability assessment of distribution system was stated. The paper also contained essential results of continuity studies for a range of sensitivity analysis and alternate configurations. Also, in [11], a validation method for reliability model was stated. The model determines component reliability data so that the predicted values of reliability indices agree with the historical data.
In another study, the author presented an algorithm in [9] that pinpoints susceptibilities in the design of distribution systems by observing the interdependencies among them. They also stated an example that illustrates interdependencies between the power and telecommunication systems.
Majority of previous publications on reliability analysis have focused on power system reliability without DGs. This research focuses on distribution system reliability with DGs. Presented in this work is an extension of the previous research work [12], which demonstrated indices used in describing power system reliability calculations.
A procedure based on [11] is used to calculate reliability indices in an unbalanced distribution system on a radial network in this work. In this procedure, the failure rate, outage duration and repair time of each load point on the circuit is determined and used to calculate the reliability indices of the system. The impact of installing DG as backup at various locations on the distribution circuit is also explored in this research.

This paper goes beyond the physical analysis of power distribution system with distributed generators; the analysis is done by checking reliability improvements by varying the distance of Distributed Generators to the Main Substation.

2. Methodology

In this work, the distribution circuit is categorized into sections and distributor laterals as shown in figure 1.

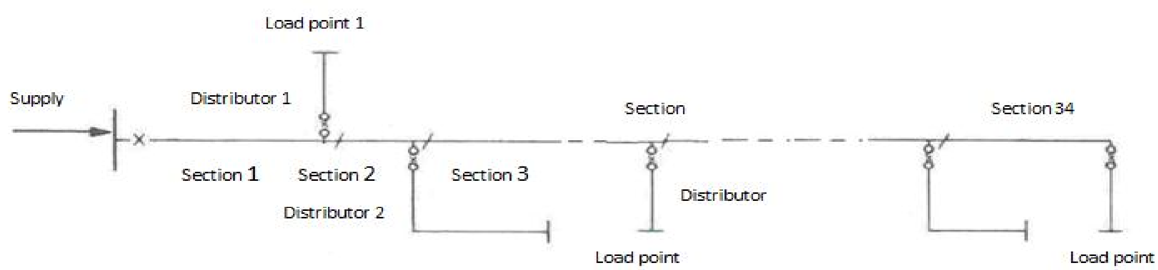

Figure 1: Definition of sections, load points and distributor laterals

To evaluate SAIDI, CAIDI, ENS and AENS of a distribution circuit, the failure rate (λ_i), average annual outage time (U_i) and average repair time (r_i) of all sections and distributor laterals must be identified. The evaluation is performed on a modeled residential area distribution circuit using MATLAB software. MATLAB software is a powerful tool for modeling, simulating and analyzing dynamic systems.
In this work, it is assumed that:

- The DGs installed on the system produce real power only.
- The disconnect and fuses are 100% available.

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- The failure rate of DG is assumed to be 0%.
- The total isolation and switching time is 2 minutes when DG is used as backup generator.
- The repair time for each section is 4 hours.
- The repair time for each distributor lateral is 2 hours.
- The failure rate for all sections on the main distribution feeder is 0.1 f*/km-yr, and that for all distributor laterals is 0.2 f/km-yr; and
- The repair time of all sections (r_i) is 4 hrs and for all distributor laterals is 2 hrs. *f represents failure frequency.
- The length of a section is l_s and that of distributor is l_d

Using the assumptions above and the length of each section and distributor lateral, the failure rate of each section and distributor lateral (λ_i) is evaluated. Then, the average annual outage time of a section or lateral i (U_i) is calculated by multiplying λ_i by r_i. Once the parameters λ_i, U_i, and r_i, of all sections and distributor laterals are determined, the failure rate of each load point, i.e. load point 's' (λ_s), can be calculated by adding the failure rates of all sections and distributors ($\sum \lambda_i$) that contribute to the unavailability of load point 's'. Based on the explanation and assumptions above, equations (1) to (12) are used [3] :

Failure rate for a section $\lambda_s = 0.1 * l_s$ (1)

Failure rate for a distributor $\lambda_d = 0.2 * l_d$ (2)

Repair time for a section $r_s = 4$ (3)

Repair time for a distributor $r_d = 2$ (4)

Outage time for a section $U_s = \lambda_s * r_s$ (5)

Outage time for a distributor $U_d = \lambda_d * r_d$ (6)

Failure rate of a load point $\lambda = \lambda_d + \sum \lambda_s$ (7)

Repair time of a load point $r = \frac{U_d + \sum U_s}{\lambda}$ (8)

Outage time of a load point

$U = U_d + \sum U_s = \lambda * r$ (9)

Total number of customers $= \sum N$ (10)

Total number of customers' interruption $= \sum \lambda * N$ (11)

Sum of customer interruption durations $= \sum U * N$ (12)

The reliability indices (SAIDI, CAIDI, ENS and AENS) used to quantify the system reliability are in equations (13) to (16)

System Average Interruption Duration Index

$SAIDI = \frac{\sum U * N}{\sum N}$ (13)

Customer Average Interruption Duration Index

$CAIDI = \frac{\sum U * N}{\sum \lambda * N}$ (14)

Total Energy Not Supplied $ENS = \sum L * U$ (15)

Average Energy Not Supplied

$AENS = \frac{\sum L * U}{\sum N}$ (16)

3. Circuit Description

The important parameters of the feeder lines are; the circuit of interest consists of 26.728 km of the main distribution feeder. The circuit comprises of 45 transformers with total capacity of 13610 kVA. The peak load used for the study is 4500 kW. It serves a total of 4308 customers including mostly residential and a few commercial entities.

The circuit is fed by 132/33 kV substation. The circuit can be divided into sections and distributor laterals as shown in Figure 1. Each distributor lateral is considered as one load point. Therefore, the system consists of a total of 34 sections and 34 laterals. Each lateral was assumed to be one load point. Therefore, the system consists of a 34 load points.

4. Result and Discussion

The Figure 2 shows a simple radial system with protection fuses on the laterals, which is the current configuration of the circuit. In this case there are no disconnects on the main line and if any section on the main distribution line fails; it would result in power outage for all the distributor laterals.

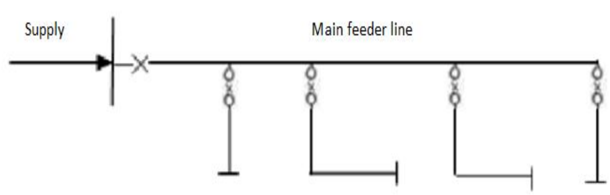

Figure 2: Simple radial system with no disconnects on the main line

Installing a DG in this configuration will not impact the reliability of the circuit since there are no disconnects on the main line and any section failure cannot be isolated. Therefore, disconnects is added on the main distribution line so that the failed section can be isolated and the rest of the loads can be supplied by the substation and DG. Figure 3 shows the same circuit with disconnects on the main line. This configuration significantly improves the reliability of the system.

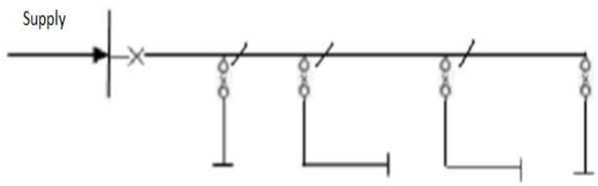

Figure 3: Simple radial system with disconnects on the main line

The Distributed Generators (DGs) to be installed on the circuit are 800kW, 1500kW and 2000kW. The DG will be installed on the main distribution line as shown in figure 4.4. The DGs will be used as backup generators.

5. Reliability Analysis

In the actual configuration of the circuit, there are no disconnects on the main line. The only protections are the fuses that connect the sections and the distributor laterals as shown in Figures 2 and 3. Hence, any fault on the main line will require the system to be isolated from the main breaker at the substation.

The reliability of each load point can be calculated by considering the impact of each section and load point on the corresponding load point. For example, the load point "Lp15" reliability calculation examined. The reliability evaluation for load point 15 is divided into two parts; sections and distributors.

Firstly, the impact of each section failure on the load point '15' reliability is considered. Any section failure will result in power outage for the load point since there are no disconnects on the main distribution line. The repair time "r_i" (hours) for each section is 4 hours. Using the length of the section, its failure rate λ_i(f/yr) is determined. Using the failure rate and repair time, the outage duration "U_i" (hours/yr) $= \lambda_i * r_i$ for each component is calculated.

Secondly, the impact of each distributor lateral failure on the load point is considered. Since, each lateral is connected to the main line through fuse; a fault on any lateral will have no impact on the reliability of load point '15' since the fuse will isolate the lateral during fault. However, if there is a fault on the load point '15' itself, its reliability impact will be added. The repair time for each lateral is 2 hours. The failure rate λ can be determined using the length of the lateral. And using the failure rate and repair time, the outage duration "U" (hours/yr) for the load point can be determined using Equation (9).

Adding the impact of each section and lateral, the average failure rate λ, average repair time r, and average outage duration U for the load point 15 can be calculated using (7), (8) and (9). Similarly, the average failure rate λ, average repair time r, and average outage duration U for all other load points can be calculated using (7), (8) and (9).

The results of (7),(8) and (9) for each of the load point together with loads(kW) and number of customers on the load points are used to evaluate the (10),(11),(12) and (15). Using these, the reliability indices (SAIDI, CAIDI, ENS and AENS) for the feeder line were determined using (13), (14), (15) and (16).

Table 1
Reliability indices result without disconnects and DG

Indices	Results
SAIDI	10.7765 *hours/customer year*
CAIDI	3.968557 *hours/customer interruption*
ENS	48474.64 *kWh/year*
AENS	11.25224 *kWh / customer yr*

Therefore, in the base case (NO DG); SAIDI is 10.7765 hrs/customer yr suggesting that system's average interruption duration for each customer is 10.7765 hrs during a year. Also, CAIDI is 3.968557 hrs/ customer interruption, suggesting average interruption duration for the customers that experience interruptions is 3.968557 hrs during a year.

Also, the ENS (energy not supplied) for the system due to failures is 48474.64kWh/yr. And finally, the Energy not supplied per customer is 48474.64kWh during a year. In the next

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sections, it will be observed that how these indices are impacted by the installation of DG and disconnects. The selected locations for the purpose of this analysis are

Table 2
Case locations

Location	Section	Remark
A	1	Start of the circuit
B	18	Middle of the circuit
C	34	End of the circuit

6. Analysis

- By using no disconnect, the impact of installing DG of different sizes on the main distribution line is explored.
- Also, by using disconnects, the impact of installing different DG sizes (800kW, 1500kW and 2000kW) on the main distribution line is analyzed
- Placing the DGs at each of the section from the fault location, a location analysis is performed to determine the best location for the placement of DG in terms of reliability indices.

7. Reliability Indices Results without Disconnect

Using the circuit configuration with no disconnects on the main distribution line and 800kW, 1500kW and 2000kW as backup generators on locations A, B and C.

Installing a DG in these situations will have no effect on the system reliability. Since in the current configuration, there are no disconnects on the main line, a fault anywhere on the main line will require the main protection scheme to trip thereby causing outage to all customers. In case of a fault on the main line, all load points will isolate themselves from the main line through the lateral protection. Therefore, the DG will not play any role in improving the system reliability and the indices are equal to the base case (NO DG) as seen in table 1.

8. Reliability Indices Results with Disconnect and using 800kW DG

Table 3 shows the reliability indices results when 800kW DG is used with disconnect

Table 3
Reliability indices results

	A	B	C
SAIDI	6.724584	5.122	5.983
CAIDI	2.476378	1.886	2.203
ENS	30240.64	23029.239	26902.689
AENS	7.019647	5.346	6.245

When 800kW DG is introduced at the location A. Adding a distributed generation (DG) at the start of the circuit will have no effect on the reliability of the system since the DG will just act as an additional source to the system. However, in case of power interruption from the main substation, the DG can be used to supply power to the system, hence increasing its reliability.

These indices differ from previous analysis since in this case, disconnects are added to the main distribution line. The indices show significant improvement due to the addition of disconnects; SAIDI improved from 10.7765 hours/customer year to 6.724584 hours/customer year (38%), CAIDI from 3.968557 hours/customer interruption to 2.476378 hours/customer interruption (38%) and ENS from 48474.64 kWh/year to 30240.64 kWh/year (38%).

Similarly when an 800 kW DG is inserted at the location B. The 800kW DG can supply loads from load point 18 to 20 completely and will not be able to take up load on 21 because the load is beyond its capacity.

With the insertion of 800kW DG at location C. In this case, since there are no loads downstream, the DG sends power upstream and supplies load points 29-34 fully.

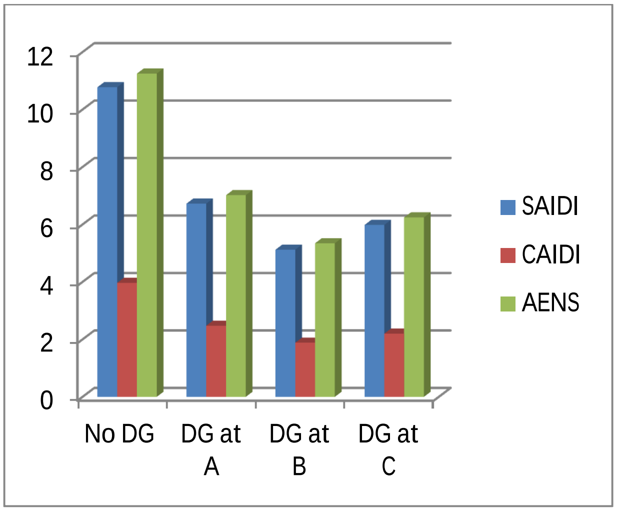

Figure 4: 800kW DG placement

Figure 4 confirms the fact that reliability is improved with the insertion of DG at locations A, B and C. The percentage improvements are shown in table 4

Table 4
percentage improvement with 800kW

	SAIDI improvement	CAIDI improvement	ENS and AENS Improvements
A	37.60%	37.60%	37.62%
B	52.47%	52.41%	52.49%
C	44.50%	44.49%	44.50%

When 1500kW DG is used, the reliability results is shown in table 5

Table 5
1500kW DG Placement

	A	B	C
SAIDI	6.724584	3.391	3.391
CAIDI	2.476378	1.249	1.249
ENS	30240.64	15239.499	15239.499
AENS	7.019647	3.537	3.537

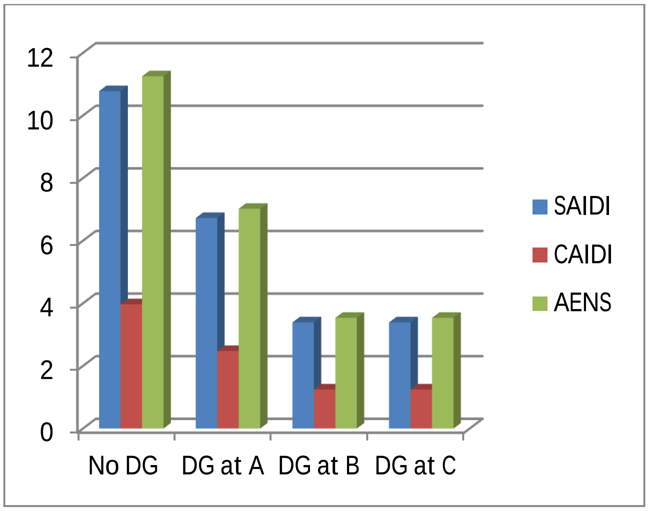

Figure 5: 1500kW DG placement

Figure 5 confirms the fact that reliability is improved with the insertion of DG at locations A, B and C. The percentage improvements are shown in table 6

Table 6
percentage improvement with 1500kW

	SAIDI improvement	CAIDI improvement	ENS and AENS Improvements
A	37.60%	37.60%	37.62%
B	68.53%	68.53%	68.56%
C	68.53%	68.53%	68.53%

When 2000kW DG is used, the reliability indices results is shown in table 7

Table 7
2000kW DG Placement

	A	B	C
SAIDI	6.724584	2.067	2.261
CAIDI	2.476378	0.761	0.833
ENS	30240.64	9281.169	10155.819
AENS	7.019647	2.154	2.357

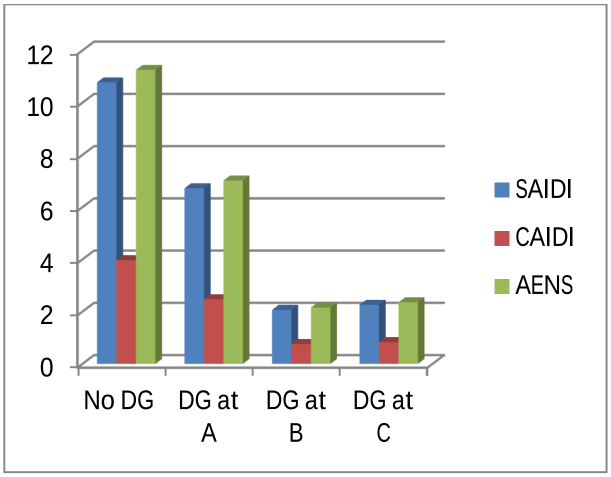

Figure 6: 2000kW DG placement

Figure 6 also confirms the significant improvement and percentage improvements are shown in table 8

Table 8
percentage improvement with 2000kW

	SAIDI improvement	CAIDI improvement	ENS and AENS Improvement
A	37.60%	37.60%	37.62%
B	80.82%	80.82%	80.85%
C	79.02%	79.01%	79.05%

Size & Location Analysis

The size of the DG and its allocation are important factors in the calculation of reliability indices. In the previous case studies, three different sizes of the large-scale DGs (800kW, 1500kW & 2000kW) were placed at 3 different locations on the main distribution line.

Now, the impact of placing the DG at all locations/sections after the faulty location is used to investigate the reliability improvement.

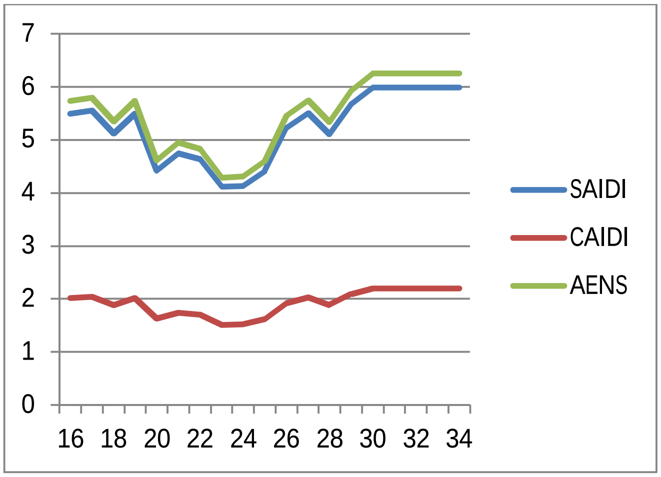

Figure 7: reliability indices vs DG(800kW) location with fault at section 15

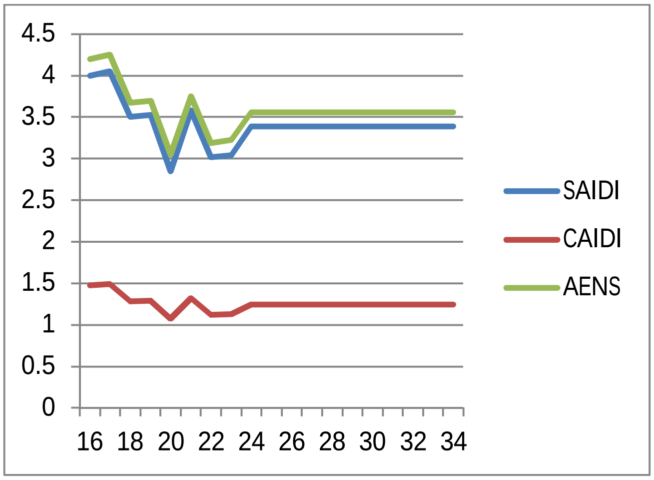

Figure 8 : reliability indices vs DG(1500kW) location with fault at section 15

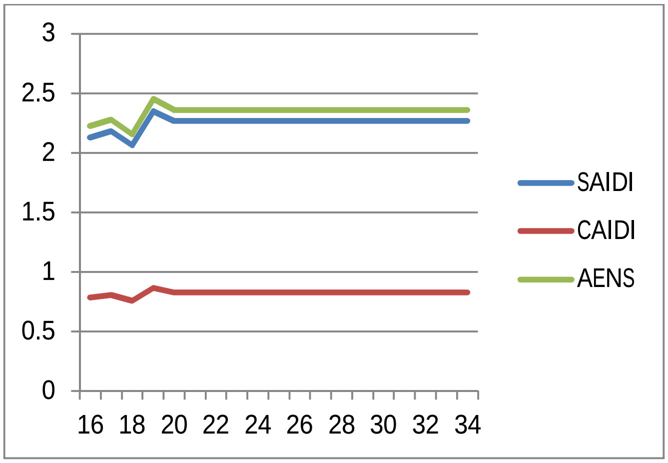

Figure 9: reliability indices vs DG(2000kW) location with fault at section 15

9. Graph Explanation

From figures 7, 8, and 9, the optimal location for the placement of 800kW DG is on section 23. The SAIDI, CAIDI, ENS and AENS all point to this location.

Similarly, the optimal the optimal location for 1500kW DG is section 20. The SAIDI, CAIDI, ENS and AENS all point to this location. The optimal location of 2000kW DG is section 18 The SAIDI, CAIDI, ENS and AENS all point to this location.

10. Conclusions

In this paper, thorough analysis on some of the impacts of distributed generation (DG) on a residential distribution network operation is conducted. Scenarios were created to analyze the data collected. This study examined the reliability of the system in two circuit arrangements (with and without disconnects on the main line) by applying DG at selected locations.

The system reliability indices will not be improved with the installation of DG on the usual distribution feeders that do not have disconnects on the main line. Also the reliability contribution of DG as a backup generator will be maximized and there will be considerable system reliability increase when disconnects are inserted on the main line. Using disconnects, DGs can supply the loads isolated from the substation in the occurrence of section or distributor lateral failures. The best location for the placement of DG is at the point where we have most load and most customers. The scenarios presented have helped toward enhancing the reliability and resilience of the power grid. This work also put forward the use of on-site Distributed Generators to complement Power Distribution. This will boost reliability and lessen risk from outages.

However, further analysis can be executed by installing DGs that produce both real and reactive power into the residential distribution network. An analysis is also recommended to be performed on meshed and more complex distribution network to investigate the reliability impact of DG.

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